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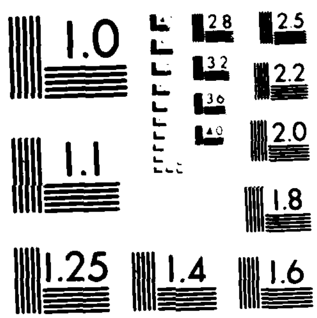


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# Special Report 83-6

April 1983

AD-A134 554

US Army Corps of Engineers
Cold Regions Research & Engineering Laboratory

# *Optimization model for land treatment planning, design and operation*

## *Part I. Background and literature review*

J.A. Baron, D.R. Lynch and I.K. Iskandar

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The material presented in Part I is intended to provide insight into the possible land treatment planning objectives, the status of land treatment research and implementation, the renovative processes that occur in the various components of these systems, and the potential for optimizing the configuration of these components. The structure and application of nine models, which include methods to optimize the regional planning, design and operation of slow-rate land treatment systems, are briefly discussed. General comments follow on the overall status of research in land treatment modeling and design and directions for future work.

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PREFACE

This report was prepared by Jaclyn A. Baron, graduate assistant, Dr. Daniel R. Lynch, Assistant Professor, Thayer School of Engineering, Dartmouth College, Hanover, New Hampshire, and Dr. Iskandar K. Iskandar, Research Chemist, Earth Sciences Branch, Research Division, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire. The report is the first of a three-part series. This part provides background information and a review of the land treatment optimization literature. A case study illustrating methods, results and sensitivity analysis is presented in Part II (Baron et al. 1983). Details of the principal mathematical model and its realization in computer form (LTMOD) are presented in Part III (Baron and Lynch 1983). This work was supported by the U.S. Army Corps of Engineers under CWIS 31732, Land Treatment Management and Operation. This report was technically reviewed by Dr. A.O. Converse and Dr. T.J. Adler of the Thayer School of Engineering, Dartmouth College.

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# OPTIMZATION MODEL FOR LAND TREATMENT PLANNING, DESIGN AND OPERATION
## PART I. BACKGROUND AND LITERATURE REVIEW

Jaclyn A. Baron, Daniel R. Lynch and Iskandar K. Iskandar

## BACKGROUND

### Planning and design objectives

The slow-rate application of municipal wastewater effluent to croplands and forest has been viewed as a means of wastewater disposal, treatment and reuse in the technical and popular literature. Although these terms are often used interchangeably, they are not synonymous and they reflect the range of perspectives from which the method is viewed. The benefits of land application of wastewater are regarded differently in various sections of this country and by individuals in various roles - the water pollution control organizations, the regional planners, the farmers and the community at large. Land application of wastewater is considered beneficial because:

1) It is a cost-effective disposal option.
2) It is less energy intensive than conventional treatment.
3) A high level of treatment of pollutants may be achieved.
4) Nutrient-rich water is not discharged to surface waters.
5) Crop yields on existing cultivated lands can be augmented.
6) It can aid in establishing new cropping activities on arid, infertile or eroding lands.
7) It can be used for irrigation, saving surface and groundwater supplies for other uses.

In short, land application of wastewater may have environmental and/or economic advantages over conventional treatment methods and may provide an opportunity to conserve water and nutrient resources. The importance associated with each of these objectives in regional planning sets the framework in which the design and operational decisions will be made, both conceptually and physically. Lynch and Kirshen (1981) pointed out that it is generally not possible to maximize the level of water treatment and the economic benefits simultaneously at a land treatment site. In planning, designing and operating these systems, it is customary to set minimum environmental standards and maximize the economic benefits (or minimize the costs) of the options within these constraints.

In the arid regions of the United States, where agricultural activities depend on a deficient and/or unpredictable water supply, wastewater effluent has value as an irrigation supplement and may be sold and distributed to private landowners. Planning the application of effluent to land becomes the classic seasonal-irrigation problem of determining the total cropped area, the cropping pattern, and the water allocation to each crop to maximize either seasonal yield or operating profits with a limited water supply.

In cool, humid areas, where precipitation is sufficient for high agricultural yields, the value of wastewater effluent as an irrigation supply is relatively unimportant. In fact, treatment by land may be considered an undesirable consumer of water valued for downstream purposes. In these areas the immediate incentive to use land application is that it is a more cost-effective treatment process than conventional alternatives. Longer-term conservation benefits, such as recycling crop nutrients, are not easily quantified. The design objective is typically to treat any given quantity of wastewater at the lowest cost. Since the treatment sites will probably be leased or bought by the municipality, this goal has usually been translated into minimizing the land area required for application (with the minimum storage requirement), or if land is inexpensive and available, minimizing the operating cost of the site. The cropping pattern is important, as the operating costs will be offset by the profits, if any, from the crops grown on the site.

Status of the science

The proliferation of land application systems in the United States has not been rapid, despite their potential benefits and the encouragement of the Environmental Protection Agency and the federal water laws (PL92-500, PL95-217). Land application systems exist mainly in the western and southwestern states (Sullivan et al. 1973, Iskandar 1978) and are especially sparse in the humid northeast (Bradley 1978). In an overview of land treatment development in the past decade, Reed and Bouzoun (1980) attributed the slow adoption of land treatment to the general lack of experience of the current generation of technical and managerial personnel with the method. Poor understanding of the concepts and processes of land treatment has inhibited wider implementation because 1) engineers and managers who

have expertise in conventional treatment processes often have little confidence in land treatment, and 2) highly conservative estimates of the renovative capacity of sites have led to exaggerated health concerns, the dismissal of many areas as physically inadequate on a long-term basis, and costly overdesign that makes the option unattractive. The lack of serious consideration and the blanket evaluation of sites as unsuitable are evident in the responses to a survey of water reuse attitudes in New England (Johnson 1979). The Public Works Survey of Facilities in the United States (Sullivan et al. 1973) concluded that conservative designs and operation, which do not take advantage of the full assimilative capacity of the land, were common at many of the sites surveyed.

Much research on land treatment processes has been conducted in the past decade, including an extensive effort by the U.S. Army Corps of Engineers led by CRREL. Long-term experiments throughout the country, including major efforts at Hanover, New Hampshire; Apple Valley, Minnesota; Utica, Mississippi; and Pack Forest near Seattle, Washington (Parker et al., in prep., Iskandar and Wright, in prep.), have added to the body of knowledge originated by The Pennsylvania State University and Muskegon County researchers. This research has improved our fundamental understanding of the biological and chemical processes that take place in land treatment. In many cases the allowable application seasons have been found to be longer, the maximum weekly application rates higher, the required storage smaller, and the renovative capacity of the land much greater than formerly believed. Also, the high potential for partial renovation in storage at the site has been recognized and quantified.

A striking example of self-defeating overdesign is the guidelines issued in the early 1970s by at least fourteen states (California, Georgia, Illinois, Minnesota, New Hampshire, New York, Oregon and Vermont, among them) requiring secondary treatment and in many cases disinfection of effluent before it is applied to the land (Ward 1975). In effect, land treatment was considered a tertiary treatment option. Since in many areas the EPA's requirements could be met with secondary treatment, these guidelines effectively precluded land treatment options entirely.

Recent research has shown that full secondary pretreatment is often not only unnecessary, it may even be detrimental to the water quality at land treatment sites (Jenkins and Palazzo 1981). Wastewater detention in

storage ponds at the site affords ample opportunity for partial biological pretreatment; prolonged detention has been found to be quite effective in removing nitrogen, BOD and pathogens, eliminating the need for prior treatment and disinfection. In 1978 the EPA relaxed its land application pretreatment guidelines, based partially on these research results. Biological in-plant primary treatment of effluent is considered sufficient for the rapid infiltration systems. At sites with unrestricted public access or where human food crops are grown that may be eaten raw, more stringent regulations apply.

Environmental quality constraints

While economic benefits of the land treatment system must be maximized, the contaminant and nutrient concentrations in the crops grown on the site, in the soil, and in the adjacent groundwater must be maintained within limits consistent with their intended use. The short-term effects of effluent irrigation on vegetation quality will ideally be evaluated early in the planning process. Either crop types that are known to retain high quality when irrigated with wastewater should be chosen, or the disposal costs associated with growing crops that may become contaminated should be recognized. At the design and seasonal-operation planning levels, good vegetation quality is usually assumed, and the focus is on achieving the level of treatment that is necessary to prevent the percolation of poor quality effluent. However, once a design and appropriate vegetation are chosen, the quality of the vegetation becomes a long-term concern. Toxic levels of metals in the crops may result as substances gradually accumulate in the soil through many years of operation; therefore, frequent monitoring of soil and vegetation quality may be necessary.

Nitrogen, phosphorus, organics, pathogens (bacteria and viruses) and trace heavy metals are removed from wastewater by land treatment. The nutrients (nitrogen and phosphorus) contribute to the eutrophication of surface water bodies. Furthermore, high nitrate concentrations in drinking water supplies are toxic to infants. High levels of organics create anaerobic conditions and affect the odor and taste of water; some organics may persist and accumulate in human bodies. Heavy metals are toxic at low concentrations. Pathogens present obvious health risks. In most areas the percolate water from land treatment sites must meet the criteria for public drinking-water supplies.

The behavior of contaminants and nutrients in slow-rate land treatment systems is well understood from experimental research on specific substances and monitoring at existing sites. Research has documented the short-term fate of these substances, and we can predict the ability of sites to sustain treatment levels over the life of a project, typically 20-50 years. The Process Design Manual for Land Treatment of Municipal Wastewater (USEPA et al. 1981) reviews the treatment processes and capabilities of soil systems suitable for slow-rate effluent application. Data from numerous sites indicate that 96-98% of the biochemical oxygen demand (BOD), 95-99% of the suspended solids (SS), 99% of the phosphorus, and nearly 100% of the trace elements and certain pathogens can be removed from either primary or secondary effluent by the soil-plant system in slow-rate systems. Many soils can continue to remove phosphorus, trace elements and pathogens without breakthrough over at least a 20-year period at the loading rates typical of slow-rate application systems. BOD or SS overloading is highly unlikely.

Nitrogen is very mobile in soils in its soluble, inorganic, $NO_3$ form; it leaches into the percolate if it is not removed by other means from the land treatment site. Ammonium is adsorbed on the soil, immobilized into organic forms, or removed by ammonia volatilization and nitrification-denitrification reactions in the soil system. In addition primary mechanisms for removing nitrogen are the biochemical processes that occur in wastewater storage lagoons, and crop uptake and removal by harvesting. Nitrogen removal efficiency varies widely, depending on the design characteristics and management of a land treatment site.

The capacity of the system to assimilate nitrogen is almost always the limiting environmental factor determining the maximum application rate of municipal effluent to land. The removal of nitrogen must be explicitly considered in evaluating design and operating options in slow-rate land treatment. The discussion of the renovative characteristics of land treatment sites will be confined to nitrogen for the rest of this report, assuming that water infiltration is less of a limiting factor.

There are no guidelines on the spatial and temporal distribution of the nitrogen concentration in the percolate from the site. Systems are usually designed to achieve an annual average nitrogen concentration,

averaged over the total application area, of 10 mg/L or less. The percolate nitrogen concentration at any time during the application season, however, should be maintained within reasonable bounds, depending on the local groundwater hydrology and use. Iskandar et al. (1976) found at an experimental site in New Hampshire that plots averaging less than 10 mg/L in the percolate for ten months of the year showed 30-40 mg/L of nitrogen in early summer due to delayed leaching of ammonium, which adhered to the soil over the cold winter months. High levels of winter application at such a site should be avoided unless consideration is given to the transient loading of the groundwater. The 10-mg/L constraint placed on nitrogen concentration in the percolate from land treatment systems may not be satisfied in traditionally fertilized systems or even in areas where no fertilizer is applied but where the nitrogen content in the soil is naturally high. These areas may be nonpoint sources of pollution, depending on the hydrology of the site. Additionally it must be remembered that the volume of percolate from land treatment sites in humid areas is greater than that under normal precipitation conditions and that the total quantity of nitrogen leached is undoubtedly increased.

Wastewater renovation in storage

Land treatment sites may include a partial-mix aeration pond for biological stabilization of the effluent if secondary treatment is bypassed; they may also include a larger facultative storage facility. The storage lagoon retains the effluent during emergencies or when application to land is limited or prohibited due to high precipitation, low crop nitrogen demand, or frozen ground. Estimates of the storage requirements in the United States based on temperature are shown in Figure 1. In cold regions it is usually considered necessary to detain wastewater in storage for several months, and the storage facility is a major design consideration.

Biological, chemical and physical processes occur in wastewater pretreatment and storage ponds, significantly affecting effluent quality. Data on these processes have recently become available through a series of EPA reports on aerated and facultative systems throughout the United States. The data from these systems have been analyzed by Reed (1981). Michigan State University operates a test facultative pond as part of their Water Quality Management Facility to evaluate wastewater treatment in lagoons and on land (King 1978).

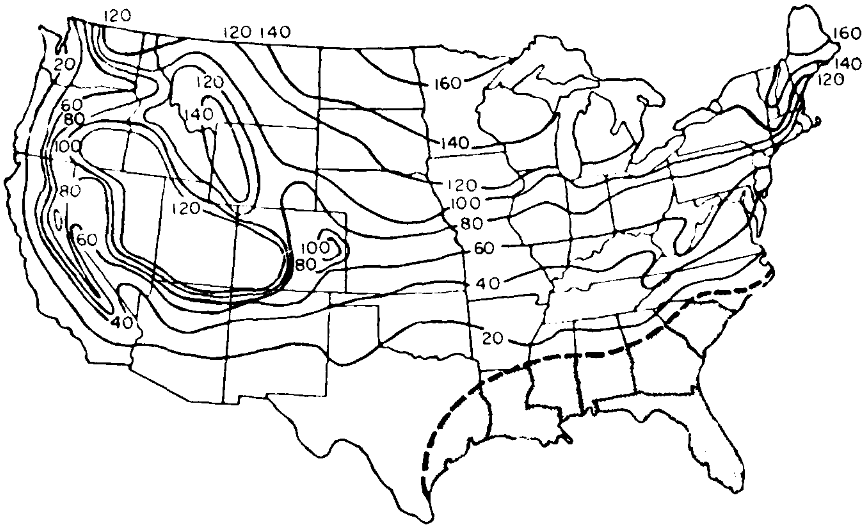



Figure 1. Estimates of the maximum storage requirement (days) due to cold. (From USEPA et al. 1981.)

The main mechanism of nitrogen loss from ponded effluent is ammonia volatilization, while denitrification, aquatic plant uptake and settling are less significant. The dissociation of ammonium ions to form ammonia gas is caused by elevated pH during the day in the presence of algae (Reed 1981). Although the processes and their interactions are complex and depend on environmental factors (temperature, light, wind mixing), pond parameters (depth, presence of algae and other plant species), and the wastewater characteristics (degree of pretreatment, organic loading), it has been possible to predict overall nitrogen removal with a simple relationship. King found that nitrogen removal at the Michigan State University facility can be described as a linear function of the total nitrogen concentration in the pond and that this concentration decreases exponentially with detention time:

$$N_t = N_o \exp(-0.03t) \tag{1}$$

where

$N_t$ = concentration of nitrogen at time t

$N_o$ = initial concentration of nitrogen

t = time in days.

Reed confirmed that a similar equation fits the data from facultative ponds in Kilmichael, Mississippi; Eudora, Kansas; Corrine, Utah; and

Peterboro, New Hampshire, during ice-free periods, assuming plug-flow conditions. However, the overall nitrogen removal was lower:

$$N_t = N_o \exp(-0.0075t). \qquad (2)$$

Equation 1 predicts a 95% reduction in nitrogen content in 120 days. Equation 2 predicts 59% removal in the same period. Reed indicated that the carefully controlled Michigan facility probably approaches the maximum practical limit for nitrogen removal in pond systems and that short-circuiting was responsible for the apparent poorer performance of the other systems.

The rate of nitrogen removal in wastewater ponds appears to be altered by seasonal temperature changes, with more renovation in the warmer months. However, the data available are from systems with long residence times, which damp out the temperature effects. Ice covers significantly inhibit volatilization and denitrification (Reed 1981). The amount of nitrogen removed from the Peterboro pond during a 140-day detention period with an ice cover was approximately half of that removed without the ice.

The data on a series of aerated ponds have not yet been completely analyzed, but they indicate that partially aerated facilites remove at least as much, and probably more, nitrogen than facultative ponds for similar detention times. In high-density aeration ponds less nitrogen would be removed because algal growth is inhibited. The nitrogen in the effluent from both faculative and aerated ponds is primarily in organic and ammonium forms (Reed 1981).

Wastewater renovation by application on land

To determine if the wastewater renovation by a given land treatment design will be satisfactory, it is necessary to predict how much of the applied nitrogen will be removed from the site, how much of the remaining nitrogen will leach into the groundwater, and how much water will percolate from the system. Models for accurately predicting percolate nitrogen concentrations throughout the year must represent biochemical transformations of nitrogen species in soils, transport of water and soluble nitrogen in the soil water, and crop uptake of water and nitrogen (Selim and Iskandar 1978, 1981). There are many, large, mechanistic and empirical models that simulate nitrogen behavior in agricultural systems. Iskandar and Selim (1978) reviewed these models and concluded that, in general, the models lack validation and are too complicated for practical use.

Selim and Iskandar (1978, 1981) and Mehran et al. (1982) developed a simplified model to predict nitrogen behavior for practical use in analyzing land treatment systems. Bradley (1978) developed empirical functions relating nitrogen concentrations in the percolate to time of year, nitrogen loading, hydraulic loading and temperature for six crops grown on a Pennsylvania land treatment site. He incorporated these functions into a model for optimizing the cropping pattern at the site. However, nitrogen simulation models and empirical relationships have rarely been used in designing and managing land treatment systems. Rather, nitrogen losses and plant uptake are estimated from experience at the site or at other sites with similar soil and climatic conditions. A mass balance, including simplified assumptions about the state of the soil nitrogen storage, is typically used to predict the quantities of nitrogen leached (Mehran et al. 1981).

Figure 2 is a schematic of the nitrogen behavior in cultivated soils. Ammonia volatilization and denitrification losses are not easy to quantify and are often considered responsible for the nitrogen unaccounted for by other means in agricultural system mass balances. Volatilization losses can be greater than 10% of the applied nitrogen if the soil pH is high and

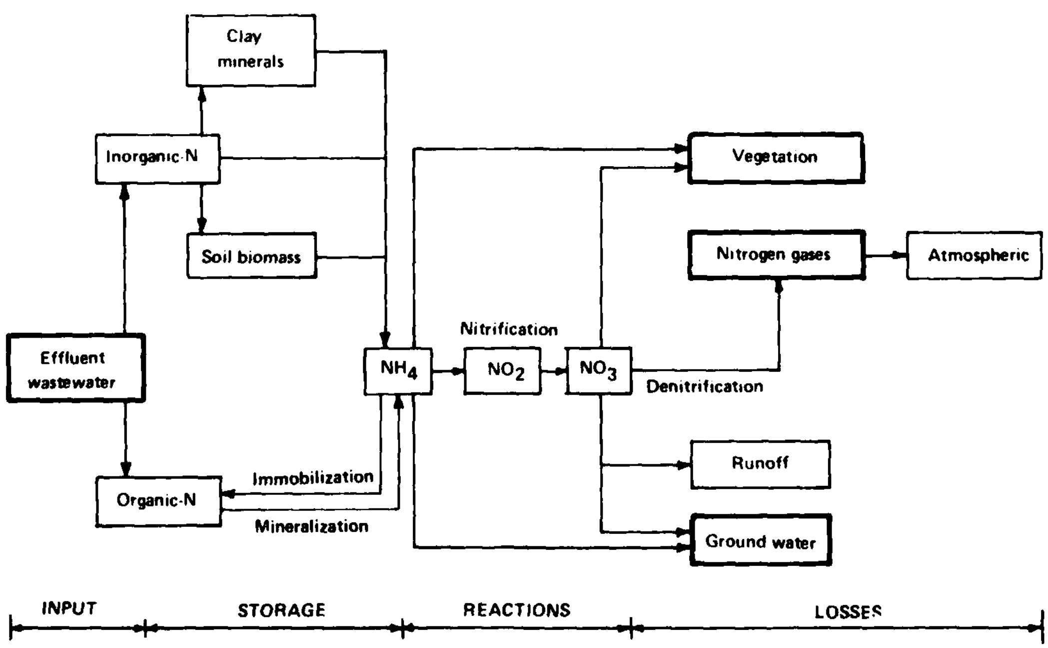



Figure 2. Nitrogen transformations in land treatment. (From Iskandar and Selim 1978).

its cation exchange capacity is low. Denitrification losses in agricultural systems typically are 10-20% of the nitrogen applied as fertilizer. Estimates of denitrification losses range from insignificant quantities in slow-rate systems (Brar et al. 1978) to 70% of the applied nitrogen in rapid infiltration systems (USEPA et al. 1981).

Iskandar and Selim (1978) pointed out that it is reasonable to expect that nitrogen losses in land treatment systems will differ from those at traditionally fertilized, irrigated sites. In traditional systems, nitrogen is applied once or twice a year and the soil is allowed to dry out between irrigations. In land treatment systems, nitrogen is applied frequently but in small quantities, and the soil moisture (especially in humid areas) is maintained at or near field capacity. Denitrification is encouraged by the application of wastewater because of the potential energy source provided by its organic carbon content. High hydraulic loadings at infrequent intervals may also encourage denitrification by alternating aerobic-anaerobic soil conditions. However, volatilization and denitrification are sensitive to many environmental factors, are not easily controlled by operating decisions, and do not constitute more than 15% of applied nitrogen in slow-rate systems.

Crop uptake of ammonium and nitrate is the major means of removing nitrogen from the land, and conversely, nitrogen uptake is the major function of the crop in slow-rate land treatment systems. The quantity of applied nitrogen that is consumed by vegetation depends greatly on the operating decisions at the site. These decisions include the seasonal cropping pattern and the intraseasonal timing of both nitrogen application and harvesting.

Seasonal nitrogen uptake by crops has been studied at many experimental sites. Of the crops studied, perennial forage grasses (e.g. reed canarygrass, fescue, ryegrass, orchardgrass and Bermuda grass) have the highest potential for renovating wastewater because of their high nutrient contents and long growing seasons. Silage corn, alfalfa, grain sorghum, permanent pasture, cotton, and grains are frequently grown for revenue on land treatment sites, but they have lower nitrogen uptake capacities. Table 1 compares crop revenue, water and nitrogen uptake potential. It has been consistently found for all crops that as the quantity of nitrogen applied is increased, the absolute quantity of nitrogen taken up increases, but the percentage uptake, or efficiency, decreases and a higher percentage

Table 1. Comparison of crop revenue, water and nitrogen uptake characteristics. (After Hinrichs 1980.)

| | Potential as revenue producer* | Potential as water user† | Potential as nitrogen user** |
|---|---|---|---|
| Field crops | | | |
| Barley | Marginal | Good | Good |
| Corn, grain | Excellent | Good | Good |
| Corn, silage | Excellent | Good | Excellent |
| Cotton (lint) | Good | Good | Excellent |
| Grain, sorghum | Good | Poor | Excellent |
| Oats | Marginal | Good | Marginal |
| Rice | Excellent | Excellent | Marginal |
| Safflower | Excellent | Good | Excellent |
| Soybeans | Good | Good | Good-excellent†† |
| Wheat | Good | Good | Good |
| Forage crops | | | |
| Reed canarygrass | Poor | Excellent | Excellent |
| Alfalfa | Excellent | Excellent | Good-excellent†† |
| Bromegrass | Poor | Excellent | Good |
| Clover | Excellent | Excellent | Good-excellent†† |
| Orchardgrass | Good | Excellent | Good-excellent†† |
| Sorghum (sudan) | Good | Excellent | Excellent |
| Timothy | Marginal | Excellent | Good |
| Vetch | Marginal | Excellent | Excellent |
| Turf crops | | | |
| Bentgrass | Excellent | Excellent | Excellent |
| Bermudagrass | Good | Excellent | Excellent |
| Forest crops | | | |
| Hardwoods | Excellent | Poor | Good |
| Pine | Excellent | Good | Good |
| Douglas fir | Excellent | Good | Good |

* The potential as revenue producers is an estimate based on nationwide demand. Local market differences may be substantial enough to change a marginal revenue producer to a good or excellent revenue producer and vice versa. Some of the forages are extremely difficult to market due to their coarse nature and poor feed values.

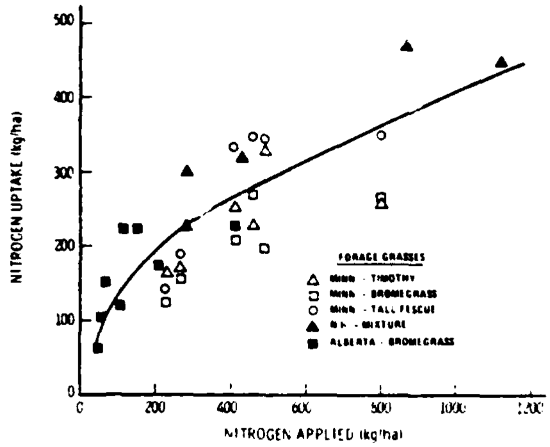
† The water user definitions are based on seasonal crop consumption in relation to alfalfa:

| | |
|---|---|
| Excellent | 0.8-1.0 |
| Good | 0.6-0.79 |
| Poor | <0.6 . |

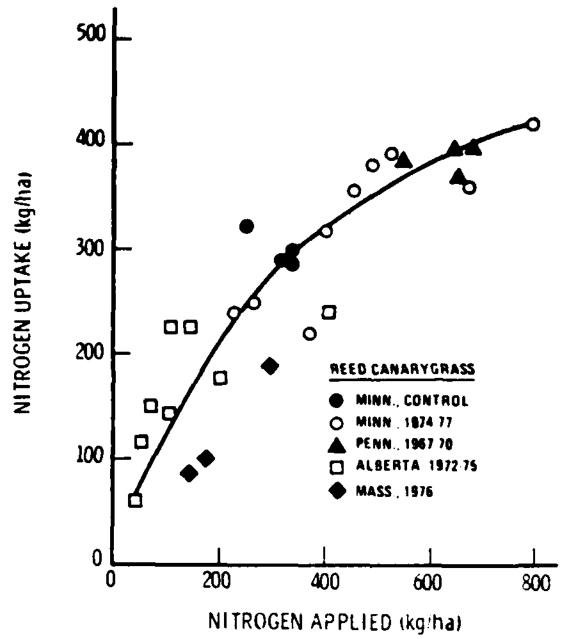
** Nitrogen user ratings:

| | |
|---|---|
| Excellent | >200 kg/ha |
| Good | 150-200 kg/ha |
| Marginal | 100-150 kg/ha |
| Poor | <100 kg/ha . |

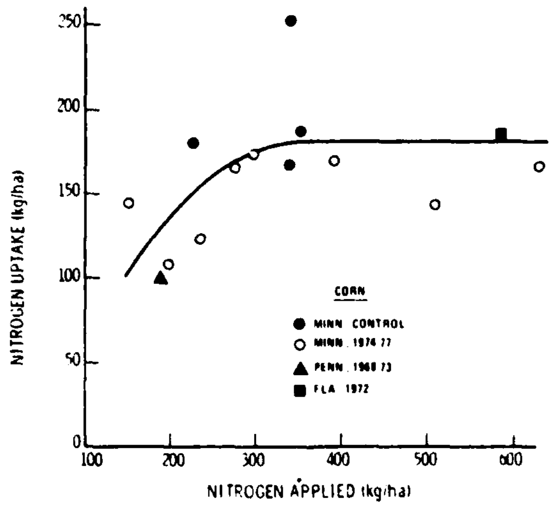
†† Depends on the percentage of nitrogen that is fixed.




a) Total seasonal nitrogen uptake by selected forage grasses irrigated with secondary municipal wastewater effluent.




b) Total seasonal nitrogen uptake by reed canarygrass irrigated with secondary municipal wastewater effluent.




c) Total seasonal nitrogen uptake by corn irrigated with secondary municipal wastewater effluent.

Figure 3. Relationship of crop uptake to applied nitrogen. (From Clapp et al. 1978.)

of that applied is leached in the percolate. Each crop has a limit to the amount of nitrogen it will remove from the soil. Figure 3 shows examples of the relationship between crop uptake and applied nitrogen at several sites. Various equations have been used to describe these relationships.

Crop uptake of nitrogen varies throughout the growing season. Data on the intraseasonal pattern of the crop uptake are sparse, but some work in this direction has recently been done for reed canarygrass, ryegrass, corn (EPA 1981) and orchardgrass (Palazzo and Graham 1981). The efficiency of nitrogen uptake during short periods of the growing season has not been studied. Koenig and Loucks (1977) approximated the intraseasonal uptake pattern of corn by multiplying the total seasonal uptake at a given nitrogen application by the percentage of the seasonal nitrogen uptake usually found in the crop at each growth stage. The typical nutrient content and yield at each growth stage for traditional agricultural practice is available for many crops.

Grasses take up large quantities of nitrogen when they are young. Frequent harvesting, although not frequent enough to greatly diminish the seasonal yield, can significantly enhance the seasonal nitrogen uptake of these species. The seasonal nitrogen uptake of grasses with different harvesting schedules has been found to vary by as much as 20% (Larson et al. 1977). The frequency of applications within a week, when equal amounts of nitrogen are applied each week, does not significantly affect either the nitrogen uptake or the crop yield (Overman 1979b).

The fate of nitrogen not removed by ammonia volatilization, denitrification or crop uptake depends on the state of the soil nitrogen storage. Organic nitrogen in the soil is transformed into ammonium (mineralization), which may be nitrified to $NO_3$ or converted back into stable organic forms (immobilization). In soils with low native nitrogen content, nitrogen added by effluent application may be incorporated into the soil storage over a period of years. In temperate soils with high nitrogen-carbon ratios, the net transfer is usually from organic to inorganic forms. The amount of soil organic nitrogen mineralized each year roughly ranges from 2 to 10%. Soils in the temperate and humid regions of North America contain from 400 kg/ha (350 lb/acre) to 10,000 kg/ha (8900 lb/acre) of nitrogen (Haitch 1973). Effluent application (assuming 40 mg/L of nitrogen, typical of primary and secondary municipal effluent) adds approximately 800 kg/ha of nitrogen to the land each year.

On lands that are newly cultivated, the immobilization-mineralization equilibrium is often disturbed and restored gradually over a period of years. The same is true of land treatment sites. Even if the applied nitrogen is initially stored in the soil, the rate of mineralization increases over the years. In general it is not good planning to allow for nitrogen buildup in the soil. Usually land treatment systems are designed and operated on the assumption that the nitrogen applied but not removed from the land will leach. Of course, it is not difficult to add net mineralization or immobilization estimates to the nitrogen mass balance if there is evidence of a significant imbalance at a particular site.

There is a delay between the time nitrogen is applied and the time it appears in the percolate. Iskandar et al. (1976) estimated that the residence time of the wastewater in the soil at a Hanover experimental site was several weeks. The nitrogen mass balance can be used to predict average monthly or annual percolate nitrogen concentrations. Predicting the fine timing of percolate concentrations on a daily or weekly basis requires a more sophisticated modeling technique.

Modeling land treatment alternatives

In land treatment design and operation there are many choices. Since the two processes (storage and application) are involved in the renovation, there is a tradeoff between the size of the storage lagoon and the land area required. Because the renovative processes are dynamic, the intra-seasonal scheduling of effluent application affects both the storage and the land area required. The cropping pattern involves tradeoffs between the revenue produced by the crops and the land area required to satisfy the environmental quality constraints. Figure 4 is a schematic of the design procedure recommended in the Process Design Manual for Land Treatment of Municipal Wastewater (USEPA et al. 1981). The feedback between the various planning components and the iterative nature of the process is evident.

The most economical design and operation plan depends on the relative costs of the effluent distribution system and the storage facility, the operating expenses associated with the system, the crop revenues, and the price of land. Pound and Crites (1973) researched the cost of land treatment system components. Young (1976) developed a computerized cost assessment program (CLAW). A land treatment module is included in the Computer Assisted Procedure for the Design and Evaluation of Wastewater Treatment

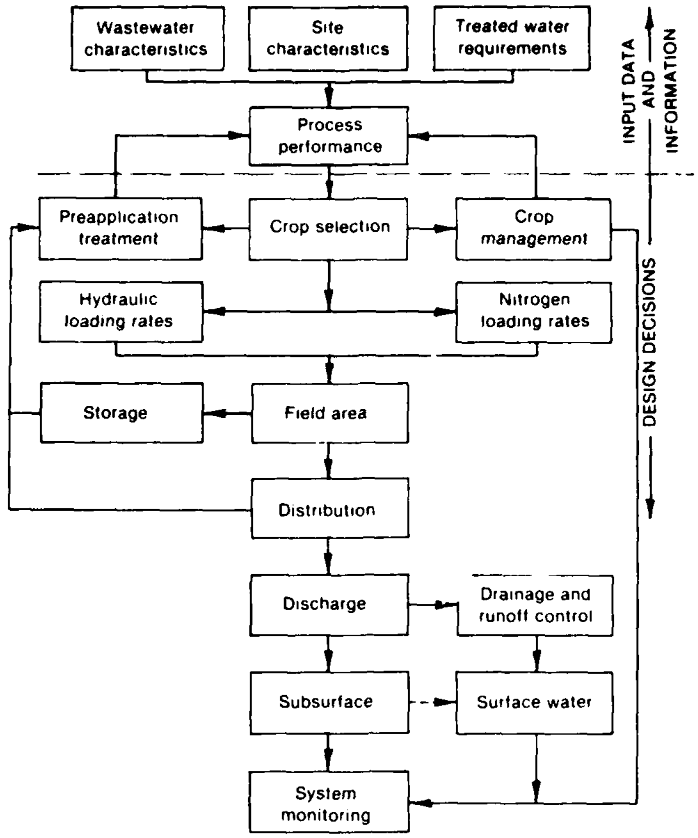



Figure 4. Slow-rate land treatment design procedure. (After USEPA et al. 1981.)

Systems (CAPDET) developed by the U.S. Army Corps of Engineers (Merry and Spaine 1977). Cost curves and equations of land treatment planning components are available in Cost of Land Treatment Systems (Reed et al. 1979).

Up to 85% of the capital cost (including the storage facility and the land) may now be subsidized by the federal government as directed in the Water Pollution Control Act Amendments of 1977. In a linear programming optimization study of a 3-mgd land treatment system in Pennsylvania (Bradley 1978), it was not worthwhile, even at the 85% federal subsidy rate, to increase the storage capacity beyond the minimum requirement (assuming one month's incoming flow for emergency and equilibration, a 365-day irrigation season, and no nitrogen transformation in storage). It was, however, worthwhile to expand the land area purchased to grow crops with higher revenue potential but with lower nitrogen uptake capacity. The

increased operating profits offset the local share of the capital investment. If there was no subsidy, the best solution would be to grow reed canarygrass, the crop with the highest nitrogen assimilative capacity, to minimize the land area required.

In any design study, one must first ask whether the cost to the local community or the total cost to society is of concern. In either case, to provide a sound basis for making decisions, land treatment models must be able to evaluate the environmental soundness and the cost of options defined by the storage capacity, the total cropped land area, the cropping pattern, the effluent application schedule, and its allocation to each cropping activity.

## MODEL DESCRIPTIONS

The models described below address the optimal planning, design and/or operation of slow-rate land application of wastewater effluent and sewage sludge to agricultural systems. The regional planning models deal with the volume of wastewater to be treated, the locations and capacities of land treatment systems, the distribution of the wastewater among the sites, and the construction schedules over the planning horizon. The example applications of the models assume that land treatment is a tertiary treatment option for secondary effluent. However, the procedures may be used to consider land treatment options for secondary treatment as well. The algorithms include a heuristic procedure for solving the classic "warehouse" problem of which sites to link to each secondary plant; mixed-integer programming to solve this problem within simple environmental constraints; and a simulation - dynamic programming procedure that examines land treatment options as well as other treatment alternatives in a more detailed study of the water quality in a region.

Design level decisions include the capacity of the storage facility and the total land area of the site. Operational decisions include the seasonal cropping patterns, the volume of effluent to be applied in each season or in shorter periods within each season, and the allocation of effluent among the cropping activities. Since the feasibility of the design options in land treatment systems strongly depends on the operation of the site, these decisions are usually prescribed in a single model. Linear programming or sequential liner programming formulations are used.

These models are similar to linear programs used in traditional seasonal-irrigation planning models. A dynamic programming formulation, similar to conventional irrigation intraseasonal scheduling models, has been developed to optimize the application of effluent to land on a weekly basis. A thorough review of mathematical modeling of irrigated systems can be found in Baron (1981). In the evaluation of land treatment options, however, environmental rather than resource constraints are emphasized.

Haith (1973)

Haith developed a linear programming model to optimize the operation of a land disposal site for sewage sludge. The simplified soil nitrogen budget developed in this model was modified in more recent work (Haith et al. 1977) to consider the application of wastewater effluent to land. In the original model the mathematical decisions are the storage of sludge in each month (which determines the required storage capacity), the sludge applied to the land in each month, and supplemental nitrogen fertilizer to apply over a planning horizon of one year. It is assumed that there is a given monthly incoming quantity of sludge of known nitrogen composition which is spread evenly over a fixed available land area with a single crop. The annual returns are maximized subject to a constraint on the total annual nitrogen leaching loss. The objective function is expressed by:

$$\text{Maximize } z = pAy - \sum_t C_t X_t - C_w W_w - C_1 A - C_f A \sum_t F_t - K \qquad (3)$$

where

$z$ = average annual return

$p$ = price of crop

$A$ = total land area

$y$ = yield per unit land area

$C_t$ = waste application (pumping) cost in month t

$X_t$ = sludge applied in month t

$C_w$ = annual cost of the waste storage facility

$W_w$ = capacity of waste storage facility

$C_1$ = annual land and cropping costs

$C_f$ = fertilizer cost

$F_t$ = fertilizer applied per unit land area

$K$ = annual fixed costs.

The soil nitrogen balance includes representations of mineralization of organic to inorganic nitrogen, crop uptake of nitrogen, and leaching to the groundwater. The incoming sludge contains mainly organic nitrogen but has an inorganic component. Separate monthly inventories in the soil are maintained for each. The soil is assumed to contain an initial organic inventory at the beginning of the year. The amount of organic nitrogen mineralized in each month $M_t$ is a fixed percentage of the organic pool, estimated from an experimentally determined annual mineralization rate and the van't Hoff-Arrhenius equation:

$$M_t = M_o \cdot \exp[0.5 \cdot E(T_t - T_o)/(T_t \cdot T_o)] \tag{4}$$

where

$M_o$ = mineralization rate at temperature $T_o$

$E$ = activation energy of the reaction

$T_t$ = average daily soil temperature in month t

$T_o$ = reference temperature at which $M_o$ is estimated in the field.

The equation distributes the mineralization over the year based on the average monthly temperatures. The inorganic nitrogen is constrained to be equal at the beginning and the end of the year. The crop nitrogen uptake in each month is an empirically determined function of the inorganic nitrogen in the soil. Absolute uptake increases, but the efficiency decreases as the available inorganic nitrogen increases. Crop yield is expressed as a function of the total annual inorganic nitrogen uptake.

The percolation water for each month is estimated from a monthly soil water balance, which includes the expected precipitation and evapotranspiration in the area. The percentage of the inorganic nitrogen leached in each month is calculated as an exponential function of the expected monthly percolate water quantity.

Once the monthly mineralization and leaching constants are determined and the yield and crop uptake of nitrogen are approximated stepwise linearly, the model becomes a linear programming problem. The model remains linear as long as some sludge storage is required during the year.

The mineralization and leaching model performed reasonably well with data for corn in upstate New York. The soil temperature was assumed to be the same as the air temperature except in months averaging below 0°C, when

the soil was assumed to be frozen. Percolation during the frozen months was deferred to the spring.

The linear programming model was applied to a sludge disposal system for a city of 100,000 people with the climate and soils similar to Ithaca, New York. The model runs included several land areas cropped with corn and allowable annual nitrogen leaching losses ranging from 70 lb/acre (78.5 kg/ha) to 116 lb/acre (130 kg/ha).

Koenig and Loucks (1977)

Koenig and Loucks developed an approximate linear programming technique to be applied when land is extremely expensive or limited. The land area is kept at the minimum size that can treat all the wastewater; the area needed is determined from the hydraulic and climatic properties of the site. The monthly application volumes are also determined this way. The maximum annual average concentration of nitrogen in the effluent applied in this regime (while satisfying the groundwater quality constraint) is determined in the linear programming. The storage capacity that will provide just enough detention time to achieve this average concentration is calculated from the water and nitrogen mass balances.

The volume of wastewater in storage is calculated from a mass balance for each month. Nitrogen removal in storage in each month is represented by a temperature-dependent, first-order reaction constant. It is assumed that the nitrogen in the pond is mostly in the nitrate form, that there is a limit to the nitrogen removal possible at long retention times, and that it is important to design the storage facility so that it does not become anaerobic. Research conducted since this model was formulated indicates that the nitrogen is mainly in ammonium and organic forms, that almost complete nitrogen removal can be attained, and that aerobic conditions are not necessary for the removal but may be needed to control the odor.

In addition to the limit imposed by the drainage capacity of the soil, the monthly application rates are constrained by an upper bound that ensures that soil infiltration will not be decreased by clogging. The water is assumed to be spread evenly on the land area with a single crop. If the average monthly temperature is below 0°C, no wastewater is applied in that month.

The simplified nitrogen budget in the model is similar to that in the Haith (1973) model. However, the monthly mineralization percentages of the

soil organic nitrogen are determined by a linear relationship based on the temperature in each month, rather than the van't Hoff-Arrhenius relationship. The model assumes that the mineralized fraction is rapidly converted to nitrate and that the concentration of nitrogen in the soil solution is the average inorganic nitrogen divided by the soil moisture content (assumed field capacity).

The site is assumed to be cropped with grass that can take up 70% of the inorganic soil nitrogen in most months of growth. Crop uptake is limited by an experimentally determined upper bound.

The procedure was applied to a situation with incoming wastewater typical of a town of 50,000 and with the climate and soils similar to Ithaca, New York. The model was run with the nitrogen concentration in the percolate constrained to be less than or equal to 10 mg/L in each month and also averaged over the year. Land areas with different drainage characteristics were also studied.

Haith et al. (1977)

Haith et al. used the physical relationships developed in their previous work (Haith 1973) in a simulation model that evaluates the performance of alternative land treatment designs. The goal is to find the least expensive combination of storage lagoon capacity, monthly irrigation rates, and irrigation land area with a single crop that satisfies the limits on nitrogen concentration in the percolate. The model includes water and nitrogen mass balances in the storage lagoon and on the land. The nitrogen mass balance includes a first-order nitrogen removal rate in storage and an estimated net mineralization rate on the land.

Each design is specified by the monthly irrigation rate per unit land area; the other system parameters are calculated. The procedure is iterative. The initial storage volume, the nitrogen concentration in the storage lagoon, and the soil inorganic nitrogen content must be adjusted until these initial conditions are reproduced at the end of one year of operation, thus representing continuous operating conditions.

The model was applied to the identical hypothetical situation as in Koenig and Loucks (1977). The simulation of 11 alternatives demonstrated the tradeoff between the removal of nitrogen in the storage lagoon and by the crop on the site.

## Lynch and Kirshen (1981)

Lynch and Kirshen used linear programming to determine the seasonal cropping patterns and seasonal effluent application volumes and distribution in a slow-rate land treatment system. The model determines the optimal annual operation of an existing facility with a given seasonal incoming effluent volume of known nitrogen concentration, a storage lagoon of given capacity, and a given land area, subject to percolation water quality constraints. The model can easily be modified to include the storage capacity and land area as decision variables if linear approximations of the capital costs are included in the objective function. The objective is to maximize the net annual operating profits.

$$\text{Maximize } Z = \sum_{ik}\sum V_{ik} \cdot A_{ik} + \sum_{k} V_{wk} \cdot D_k - C_{irr} \cdot IRRM - \sum_{k} OM_{irr} \cdot IRR_k$$
$$- \sum_{k} OM_f \cdot FERT_k - \sum_{ik}\sum C_{ik} \cdot A_{ik} \tag{5}$$

where

$V_{ik}$ = revenue from sale of crop i in season k

$A_{ik}$ = area planted of crop i in season k

$V_{wk}$ = revenue from sale of renovated water in season k

$D_k$ = water percolating from irrigation area in season k

$C_{irr}$ = capital cost of supplemental irrigation system

IRRM = capacity of supplemental irrigation system

$OM_{irr}$ = operation and maintenance cost of supplemental irrigation system

$IRR_k$ = volume of supplemental irrigation water in season k

$OM_f$ = cost of applying supplemental fertilizer

$FERT_k$ = supplemental fertilizer applied in season k

$C_{ik}$ = variable cost of crop i in season k.

The model solution provides the applied effluent volume, the storage volume, the land area of each crop, the drainage from the area, the nitrogen leached to the groundwater, the supplemental irrigation, the fertilizer applied in each season, and the capacity of the supplemental irrigation system. The solution is subject to the following constraints: 1) the entire annual wastewater flow must be treated, 2) the available land restriction must be met, 3) the drainage capacity of the soil must not be

exceeded, 4) the concentration of nitrogen in the percolate must meet the water quality standard (the percolate nitrogen concentration is averaged over the site in each season), 5) the storage in each season cannot exceed the capacity of the storage lagoon, 6) the effluent applied in each season cannot exceed the capacity of the irrigation system, and 7) the storage volume at the end of the year must equal the storage volume at the start of the year. The authors indicated that a constraint on crop heavy-metal uptake is implied in the objective function. Crops that take up significant quantities of heavy metals may have low prices or costs associated with their disposal.

The soil water and nitrogen balances are updated on a seasonal basis. It is assumed that 1) the soil is maintained at field capacity throughout the year, 2) any nitrogen in the applied effluent not taken up by crops is leached in the percolate in the season, and 3) each crop takes up a fixed amount of nitrogen in each season and has a fixed yield value for each acre grown, regardless of the level of effluent application. Nitrogen uptake efficiency is not considered. If the nitrogen demand of the crop is not satisfied by the effluent application, supplemental fertilizer must be applied.

The concentration of the nitrogen in the storage lagoon in each season must be estimated separately and must be exogenously supplied in the linear programming. Since this concentration depends on the application schedule, an iterative procedure is necessary to achieve consistency between the model inputs and the optimal solution.

The model was applied to the identical 5-mgd system as the Haith et al. (1977) model, with soil, climatic and crop data from Hanover, New Hampshire. No effluent is applied in the winter months, and percolation of winter precipitation is deferred until spring. The crops considered included alfalfa, reed canarygrass and barley. The sensitivity of the solutions to the percolate water quality constraint (varied from 5 mg/L to 15 mg/L nitrogen content) was examined.

Lynch and Kirshen also developed an intraseasonal scheduling model for land treatment systems intended for use in conjunction with their interseasonal (yearly) planning model. The model determines the optimal weekly effluent application depths and distribution among the crops throughout a single growing season. The land area of each crop and the wastewater

storage levels at the beginning and end of the season are set by the results of the interseasonal planning model. The dynamic programming formulation contains nonlinear crop-water-nitrogen relations that were simplified in the interseasonal linear program.

Two benefits are recognized in the objective function, which maximizes economic return: 1) the value of the total seasonal yield of the crops and 2) the value of the renovated wastewater. The seasonal yield of each crop is the sum of the growth contributions in each time period. The growth contributions in each period are functions of the crop water and nutrient uptake. The economic contribution of the renovated wastewater depends on the amount of water not consumed by the crop, creating a tradeoff. Irrigation costs are not included in the analysis.

A mass balance at the lagoon determines the effluent storage volume at the end of each time period. The allowable storage levels are limited by the capacity of the lagoon. The wastewater applied in each period is limited by the irrigation system capacity. The total seasonal amount of wastewater applied must equal that prescribed by the linear program results.

A nonlinear mass balance determines the average concentration of each nutrient in the storage lagoon (and thus the concentration in the applied effluent) in each time period. The nutrient balance includes the amount removed by internal processes in the lagoon. For phosphorus this is assumed to be nil; for nitrogen a first-order decay constant is used.

Crop water uptake is an exponential function of the quantity of water available. Uptake efficiency decreases as the applied effluent increases in each period. Crop nutrient uptake is similarly an exponential function of the quantity of nutrient available to the crop. Any supplemental irrigation and/or fertilizer additions indicated by the planning model, as well as precipitation, are included in the available resources to the crop.

The groundwater quality constraint may be based on 1) the concentration of each nutrient in the leachate for each crop in each period, 2) the spatially averaged concentration of each nutrient in all the leachate from the treatment site in each period, or 3) the absolute value or total discharge of each nutrient in each period.

Solution of this problem with its many state variables is simplified by decomposing the spatial and temporal domains. First, for an array of

feasible values of the total effluent and its nutrient concentrations to be applied in a period, the optimal distribution of the effluent among the crops is determined by dynamic programming. These programs have a single decision variable -- the amount of effluent to be applied to each crop or stage. The state variable is the amount of water remaining at each stage; an additional state variable for each nutrient may be required, depending on how the groundwater quality constraint is imposed. Once the optimal distributions among the crops are available, the complete problem of how much effluent to apply in each period (the decision variables) is solved. In this dynamic program the state variables are the amount of wastewater storage and the concentration of each nutrient in storage in each period or stage.

The model was applied to the spring season of the situation described for the planning model. The crops were reed canarygrass and barley.

Bradley (1978)

Bradley developed a linear programming model that determines the optimal spray irrigation area and storage capacity, as well as the annual cropping pattern and effluent application distribution in a slow-rate land treatment system. The model distinguishes between the annual local costs (those that are not subsidized by the Federal government and are paid by local municipalities) and the social (total) cost of the project. Solutions for lowest local and total costs are generated to assess the impacts of the subsidies on municipal design and operating choices and their implications for increasing social costs. The objective function includes land, labor, capital, materials and energy costs associated with sewage transmission, preapplication treatment, wastewater storage, pumping, irrigation systems, land clearing, a buffer zone, service roads and fencing, monitoring and administration, engineering and legal services, and net revenues from the cropping activities. All cost curves except those associated with the cropping activities are from Young (1976).

The required storage capacity is solely a function of the permissible application rates determined by the renovation achieved by the cropping pattern options. The model ignores wastewater renovation in storage.

Each cropping activity consists of irrigating a particular crop at a specified weekly rate for a specified growing season length. Different irrigation levels and growing seasons may be associated with the same

crop. Each cropping activity produces an arrival flow of treated wastewater and a level of crop yield. The monthly concentrations of nitrate in the leachate associated with each cropping activity are estimated from empirical functions obtained from extensive experimentation and multiple regression analysis. The nitrate leaching depends on time of the year, nitrogen loading rate, hydraulic loading rate, temperature and crop. Lagged-variable specifications are considered in the analysis. Crop yields at different irrigation levels are estimated by simple averages obtained from experiments. Timber yields of forest lands are based on estimates of the site index (which indicates the average height attained by 50-year-old trees of a particular type) at different effluent irrigation levels. These are also obtained experimentally.

The constraints are: 1) all annual incoming effluent must be treated, 2) the average annual nitrate concentration in the leachate must not exceed 10 mg/L, and 3) a minimum storage capacity is specified, which may be used for flow equalization, emergency storage and cold-weather storage.

Annual nitrate leaching models and yield estimates were developed for alfalfa, corn, reed canarygrass, natural vegetation, mixed oats and red pine at different irrigation levels. The linear programming model was applied to a 3-mgd incoming wastewater flow with a nitrogen concentration typical of secondary effluent treated in an aerated lagoon. The climatic conditions are typical of central Pennsylvania. The minimum storage capacity was set at one month's expected effluent volume. Thirty-three cropping activities were considered. The minimum cost solutions (local and total) were obtained for various capital subsidization rates, land prices, interest rates, crop prices and irrigation restrictions on the maximum acreage devoted to each cropping activity.

Haith and Chapman (1977)

Haith and Chapman developed a model to screen the best practicable wastewater treatment alternatives. The procedure evaluates the distribution of a specified volume of secondary-treated wastewater among the options of application to a land treatment site, direct discharge into a river, and tertiary treatment by filtration, nitrification or both sequentially. The best alternative is defined as the lowest cost solution such that 1) all wastewater is disposed of, 2) water quality standards are met

for dissolved oxygen (> 5 ppm) at all points in the river, and 3) nitrate concentrations in the groundwater are acceptable at the land treatment site.

The decision variables in the land treatment (by irrigation) sector of the model include 1) the daily wastewater flow to the site and 2) the irrigated land area, which determines the average weekly wastewater application. The constraints are: 1) the nitrogen concentration in the percolate must be less than 10 mg/L on a seasonal basis (the nitrogen concentration in the incoming effluent, the precipitation, the evapotranspiration, and the crop nitrogen uptake at the site are considered in formulating this constraint), 2) the seasonal nitrogen application must be at least equal to the crop uptake, and 3) the weekly effluent loading rate must be less than the drainage capacity of the soil.

The annual costs of land treatment are expressed as nonlinear functions of the area irrigated and of the daily wastewater flows to the site. The costs include capital contributions and operating and maintenance costs associated with the pipeline, the storage lagoon, irrigation application, the price of land, crop production, and the benefits from crop sales. The land treatment total-cost fraction is inserted in an objective function to minimize the sum of the costs of all of the alternatives. The cost of all treatment options except land treatment are expressed as nonlinear functions of the daily wastewater flow.

Two solution procedures are proposed for this nonlinear model. The first is a simulation approach that evaluates and compares proposed alternatives. The proposed flows to each treatment alternative (or no treatment) are set, and the irrigation area for land treatment is chosen so that the drainage and groundwater quality constraints are satisfied. The dissolved oxygen characteristics in the river are checked, assuming that all untreated and treated water except that used in land treatment is discharged to the river. The total cost of the scheme is then computed.

The screening model can be simplified and solved by dynamic programming, in which the decision variables are the amount of wastewater allocated to each stage and the treatment process. The entire problem is then expressed in terms of the volume of wastewater treated in each process.

The method was applied to a hypothetical situation where treatment options are being considered for a 10-mgd secondary treatment plant effluent for the three low-flow summer months. The data for the land treatment

option using corn is consistent with conditions in the northeast United States. The costs of individual treatment types and various combinations of treatment types were evaluated by simulation. Dynamic programming was used to test combinations of treatment types and to test the sensitivity of the solution to the distance from the wastewater source to the land treatment site.

Markland et al. (1976)

Markland et al. developed a regional planning scheme for tertiary treatment of wastewater by application to land. First, a set of suitable locations are identified. Then, mixed-integer programming is used to determine which treatment sites should serve which secondary plants, when construction of the sites should be initiated, and when the capacity should be expanded.

Projections of future land use (industrial, residential, commercial and public) are obtained by a water-policy and land-use computer-simulation model. Potential sites are identified by 1) subjective estimates of the resistance to land disposal site development in the vicinities based on the land use and 2) a sparsity index, which indicates the percentage of land that is available. The more desirable sites are examined in further detail, and the final selections consider soil suitablity, topographic features and geographic distribution.

A large-scale mixed-integer program is used to choose between the alternative sites in a regional cost-benefit analysis in which the forecast quantities of wastewater generated from each secondary plant are specified. The objective is to minimize net present costs, including the initial capital investments at each site and the costs associated with expansion, operation of the sites, pipeline construction and transportation, benefits from the sites, and salvage values at the end of the projects.

The solution constraints are: 1) one facility may be built at each site, 2) the average daily effluent application at each site cannot exceed capacity, 3) the total available land area at each site is limited. 4) all wastewater from the secondary plants must be treated, 5) a minimum amount of wastewater must be treated in each time period, 6) capital expenditures in each period cannot exceed available funds, 7) groundwater quality at each site must be preserved, 8) groundwater quality in the region must be

preserved, 9) one pipeline may be constructed from each secondary plant to each land treatment site, and 10) daily flows are limited by pipeline capacity. The costs are linear functions of the decision variables (the total wastewater flow to each land treatment site and the area developed at each site in each period).

The model was applied to the St. Louis metropolitan area over a 50-year planning horizon. The study included forecasts of the location and capacities of 13 secondary facilities and 19 potential spray irrigation land treatment sites for 10 five-year periods.

The authors indicated that the program is well documented and user oriented. However, the required computer time is quite large. The groundwater quality forecasts are extremely simplified; they are based on estimates of the percentage of the total wastewater flow that will pollute the groundwater at each site. More detailed information about the biological and chemical processes at each site could improve the model. Overland flow, fast-rate land treatment, and other tertiary treatment options can be included in the general procedure.

Chiang (1977)

Chiang extended a heuristic algorithm for regional wastewater planning developed in previous work (Chiang and Lauria 1977) to include land application of wastewater. The procedure determines the location, timing and scale of regional land treatment sites and sewer piping construction. The problem is simplified by considering just one planning period (the 20-year horizon required by the EPA cost-effectiveness analysis guidelines), as the author indicates that overall present-worth costs are not sensitive to large changes in the capacity design period. The analysis includes only cost comparisons; environmental quality is not addressed.

The procedure begins with a proposed plan, which is based on sound engineering judgement of which land treatment sites should serve which secondary treatment plants. The initial plan is evaluated for possible improvements in a two-step procedure. In step one, for each plant served by a site, the routine conducts a marginal cost analysis to determine if savings are possible by closing the site and opening an alternate site. A similar analysis is conducted for possible improvements by opening alternate transportation routes while the current site remains open. After all plants have been examined, the procedure is repeated until no further

improvements are possible. In step two, all possible pairs of land treatment sites are considered, one open and one closed. All the closed sites are ranked in order of potential cost savings if opened, and the best one is opened. If improvement is made, the routine returns to step one. The two steps are repeated until no further improvement is possible.

The purpose of the procedure is not to reach one least-cost solution but to generate a range of good, low-cost solutions. Different initial solutions will yield different low-cost alternatives. The algorithm is applied to a simplified hypothetical situation with three land treatment sites, three treatment plants, and a network of possible piping routes.

SUMMARY AND CONCLUSIONS

The structure and application of nine models that optimize various aspects of the design and operation of effluent-irrigated systems have been reviewed above. Major areas in which basic understanding of the physical system is necessary to formulate these models, as well as the data required to use them effectively and the major issues involved, are indicated. From this overview, the following conclusions may be drawn:

1) Our basic understanding of the crop-soil-water-nitrogen relationships is generally sufficient to formulate irrigation models, although specific data may not be available for particular applications. The evapotranspiration over the course of a growing season has been well studied in many areas of the United States, and transferable water production functions have been developed for many crops. Unfortunately, data on the intraseasonal distribution of crop nitrogen requirements and uptake are sparse. The ability to predict the crop uptake of nitrogen at each point in time over the growing season at different application levels, and the yield dependence on this uptake is necessary for land treatment modeling. Further work is needed in this area.

2) The land treatment design models, which are an outgrowth of the models used in the irrigation field, are linear programs or simulation procedures. In land treatment models it is necessary to define the efficiency of crop uptake of water and nitrogen, the leaching characteristics at different levels of irrigation, and the renovation of the effluent in storage. Detailed representation of these nonlinear relationships can be inserted into simulation procedures. However, simulation approaches can generate good, but not necessarily optimal, solutions. When multicrop

options are analyzed (and they should be in thorough land treatment design), the large number of alternatives increases the already difficult task of finding the best one.

In the direct-optimization, linear-programming models, the nonlinearities of crop water and nitrogen uptake and the production function must be approximated, the application options must be broken down into a discrete small set, or, as in the Bradley (1978) model, a large amount of site-specific experimental data must be obtained. The mass balance of nitrogen in storage, which is important in the design, is extremely difficult to represent in a linear programming model and has required an inefficient, combined simulation-optimization procedure.

Advances in systems analysis have made a number of sophisticated optimizing algorithms commercially available (e.g. geometric, nonlinear programming), which are well suited to solving problems of this kind. This newer technology should be used in irrigation and land treatment planning. It is also potentially capable of solving multicrop intraseasonal scheduling and seasonal allocation and cropping pattern planning problems simultaneously.

3) Embedded in much of the land treatment design literature is the assumption that it is economically desirable to minimize the capacity of the storage facility. The minimum irrigation area required to meet the environmental quality constraints is then calculated based on optimal system operation and this storage volume. The storage cost is high in land treatment; however, the cost of many of the other components (service roads and fencing, monitoring wells, pumping and transmission of the effluent from storage throughout the irrigation site, and the cost of irrigation itself) depend on the land area required. Minimizing the storage volume may not be desirable in all situations. The expansion of the storage facility may significantly reduce the irrigation area required because wastewater renovation in storage increases with higher residence times. The cost characteristics of the feasible range of optimal storage-land combinations should be examined to see if there is indeed a tradeoff between the land area required and system cost along the entire range of alternatives, and to determine the magnitude of the penalties for choosing storage-land combinations other than the optimal one. It may be that alternatives requiring less extensive land use are cheaper than, or nearly

equivalent to, alternatives with low storage volumes. Since land availability has been cited as a major roadblock in implementing land treatment systems, investigating the design flexibility in this area may prove fruitful.

4) Implementing operating options, such as the ability to bypass the storage facility in times of high crop nitrogen demand (which has been suggested by several researchers) and winter application in cold regions (which has been shown to be hydraulically feasible), may also have beneficial effects on the design and cost of slow-rate land treatment systems. These questions have not received sufficient attention.

There is no doubt that confidence in and knowledge of land treatment systems have incresed dramatically over the past decade. The greatest benefits from this research and experience will be realized by recognizing the expanded set of design and operating options that are available, and by incorporating this flexibility in applying the technology. To this end, the model and case study described in Parts II and III of the present series (Baron and Lynch 1983, Baron et al. 1983) have been pursued.

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